The Anticipated Supernova Associated with GRB090618

Shlomo Dado[1] and Arnon Dar[2]

ABSTRACT

We use the cannonball model of gamma ray bursts (GRBs) and public data from the first day of observations of GRB 090618 to predict its X-ray and optical lightcurves until very late times, and, in particular, the emergence of a photometric and spectroscopic signature of an SN akin to SN1998bw in its optical afterglow with an anticipated peak brightness of magnitude$\sim$23.2 in the R band around July 10, 2009, if extinction in the host galaxy can be neglected.

1. Introduction

The relatively nearby bright gamma ray burst (GRB) 090618 that was discovered by the Swift Broad Alert Telescope (BAT) on June 16, 2009 at 08:28:29 UT (Schady et al. 2009a) provides another good opportunity to investigate the association of long duration GRBs with supernova explosions and to test theoretical models of long GRBs (e.g. Malesani 2009, Dado and Dar 2009). Two such models have been used extensively to analyze GRBs and their afterglows (AGs), the fireball (FB) model (for recent reviews see, e.g., Mészáros 2006; Zhang 2007) and the cannonball (CB) model (e.g. Dado & Dar & De Rújula 2002, hereafter DDD002, Dar & De Rújula 2004, hereafter DD2004; Dado & Dar & De Rújula 2009a,b, hereafter DDD2009a,b, and references therein). The two models are quite different and at most only one can correctly describe GRBs. Until recently, the FB model has been widely accepted as that one. However, the rich data on GRBs and their afterglow accumulated from space based observations, in particular from the Swift and Fermi satellites, from early time observations with ground based robotic telescopes and from late-time follow-up observations with large telescopes, have challenged this prevailing view (DDD2009a and references therein): Synchrotron radiation (SR), the only radiation mechanism in the original FB model, cannot explain simultaneously the prompt optical emission and the hard X-ray and

[1]dado@phep3.technion.ac.il
Physics Department, Technion, Haifa 32000, Israel

[2]arnon@physics.technion.ac.il
Physics Department, Technion, Haifa 32000

gamma-ray emission from GRBs which were both well measured in some bright GRBs such as 990123 and 080319B. The prompt hard X-ray and gamma-ray pulses cannot be explained by synchrotron radiation from internal shocks generated by collisions between conical shells. Neither can SR explain their typical energy, spectrum, spectral evolution, pulse-shape, rapid spectral softening during their fast decay phase and the established correlations between various observables. Moreover, the early time high energy emission is uncorrelated to the prompt keV-MeV emission and lags behind it. As for GRB afterglow (AG), contrary to the predictions of the FB model, the broad band AG of GRBs is highly chromatic at early times, the AGs of the brightest GRBs do not show jet breaks, and, in canonical AGs where breaks are present, they are usually chromatic and do not satisfy the closure relations expected from FB model jet breaks.

The situation concerning the CB model is different. The predictions of the model which were derived in fair approximations from its underlying assumptions were shown to describe correctly the main observed properties of GRBs and to reproduce successfully the diverse broadband lightcurves of large representative sets of both long GRBs and XRFs (e.g., DDD2009a and references therein) and short hard bursts (DDD2009b), in particular of relatively nearby bright GRBs with precise and well sampled lightcurves. Here we repeat the exercise of predicting from early time observations the entire late time behaviour of the afterglow of the recent, relatively nearby, bright long GRB 090618 and the emergence of a photometric and spectroscopic signature of an SN akin to SN1998bw in its lightcurve before their observations.

2. GRB090618

At 08:28:29 UT, the Swift Burst Alert Telescope (BAT) triggered and located the bright long duration gamma ray burst (GRB) 090618 (Schady et al. 2009a) at redshift z=0.54 (Cenko et al. 2009b). About 90% of the GRB energy measured by BAT was emitted within T90=113s (Baumgartner et al. 2009). The Swift X-ray telescope (XRT) began follow up observations of its X-ray lightcurve (see Fig. 1) 124 s after the BAT trigger and its UVO telescope detected its optical AG 129s after trigger (Schady et al. 2009b). The burst was detected also by AGILE (Longo et al. 2009), Fermi GBM (McBreen et al. 2009), Suzaku WAM (Kono et al. 2009), KONUS-WIND and KONUS-RF (Golenetskii et al. 2009). The burst light curve showed a smooth multipeak structure with 4 prominent peaks (one followed by three much brighter overlapping peaks) with a total duration of 160 s. Significant spectral evolution was observed during the burst. The spectrum at the maximum count rate, measured from T+62.720 to T+64.0 s, was well fitted (Golenetskii et al. 2009) in the 20 keV

- 2 MeV range by the Band function (Band et al. 1993) with a low-energy photon index -0.99 (-0.06, +0.07), a high energy photon index -2.29(-0.5, +0.23), and peak energy Ep=440±70 keV while the time integrated spectrum had a low-energy photon index -1.28$\pm$.02 , a high energy photon index -2.66(-0.2, +0.14), and a peak energy Ep=186±8 keV. The isotropic equivalent energy in the 8-1000 keV band was E_{iso}=2.0 $\times$ 10^{53} erg (standard cosmology).

The bright optical afterglow of GRB090618 was first detected by the ROTSE III robotic telescope 23.9 s after the BAT trigger (Rujopakarn et al. 2009) and by the Palomar 60-inch telescope (Cenko et al. 2009a), the Katzman Automatic Imaging Telescope (Perley et al. 2009, Li et al. 2009) and the UVO Telescope aboard Swift (Schady et al. 2009a) within 2 minutes after trigger. Absorption features which were detected in its bright optical AG with the 3m Shajn telescope at Lick observatory yielded a redshift of z=0.54. Its optical AG was followed up by many telescope and reported shortly after in GCN circulars (see Table I). Its R band light curve reported in these GCN circulars before June 27, 2009 is shown in Fig. 2 .

3. The CB model

In the cannonball (CB) model (DDD2002, DD2004, DDD2009a, and references therein) long-duration GRBs and their AGs are produced by bipolar jets of highly relativistic CBs of ordinary matter which are ejected (Shaviv & Dar 1995, Dar & Plaga 1999) in core-collapse supernova (SN) explosions akin to SN 1998bw (Galama et al. 1998). Their prompt MeV gamma-rays and hard X-rays are produced by the thermal electrons in the CBs' plasma by inverse Compton scattering (ICS) of glory photons - photons emitted/scattered into a cavity created by the wind/ejecta blown from the progenitor star prior to the SN. When the CBs cross the wind/ejecta and coast through the interstellar medium (ISM) behind it, the electrons of the ionized gas in front of them that are swept in and Fermi accelerated by the CBs' turbulent magnetic fields emit synchrotron radiation (SR) which dominates the 'prompt' optical emission and the broad band afterglow emission. ICS of the SR radiation by these electrons and the decay of π^0's produced in collision between the swept-in wind and ISM protons and the ambient CB protons produce the 'prompt' high energy emission simultaneously with the optical emission. Within the CB model, the above radiation mechanisms with the burst environment suffice to provide a sufficiently accurate description of the observed radiations from GRBs at all times and all detected wavelengths.

3.1. The optical lightcurve

In the CB model, the observed optical light has three origins: the ejected CBs, the SN explosion, and the host galaxy. The optical light curve is the sum of their energy flux density:

$$F_{AG}[\nu,t] = F_{CB}[\nu,t] + F_{SN}[\nu,t] + F_{HG}[\nu,t]\,. \tag{1}$$

The contribution of the host galaxy, F_{HG}, is usually extracted from very late time observations when the CB and SN contributions become negligible. In the case of GRB090618, a faint object is visible in the SDSS r and i frames at the position of the optical afterglow, likely its host galaxy. Compared to nearby SDSS stars, its r magnitude was estimated by Malesani (2009) to be 22.7±0.3.

The energy flux density of an SN like SN1998bw with an energy flux density $F_{bw}[\nu,t]$ at redshift $z_{bw}\!=\!0.0085$ (Galama et al. 1998) placed at a redshift z is given by (e.g., DDD2002),

$$F_{SN}[\nu,t] = k\,\frac{D_L^2(z_{bw})}{D_L^2(z)}\,\frac{A_{SN}[\nu,z]}{A_{BW}[\nu,z_{bw}]}\,F_{bw}[k\nu,t/k]\,, \tag{2}$$

where $k\!=\!(1\!+\!z)/(1\!+\!z_{bw})$, $A(\nu,z)$ is the attenuation of the observed SN light at frequency ν arriving along the line of sight, and $D_L(z)$ is the luminosity distance to redshift z (we use the standard cosmology with $\Omega_M\!=\!0.27$, $\Omega_\Lambda\!=\!0.73$ and $H_0\!=\!71\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$).

In the CB model (DDD2009a,b and references therein) the afterglow emission begins when the CBs encounter the wind/ejecta of the progenitor star. It is dominated by synchrotron radiation (SR) from the electrons of the ionized wind and interstellar-medium in front of the CBs which are swept in and Fermi accelerated by the CBs' turbulent magnetic fields which we assume to be in approximate energy equipartition with their energy.

The SR, isotropic in the CB's rest frame, has a characteristic frequency, $\nu_b(t)$, the typical frequency radiated by the electrons that enter a CB at time t with a relative Lorentz factor $\gamma(t)$, and spiral around its equipartition magnetic field (with the incident protons). In the observer's frame:

$$\nu_b(t) \simeq \frac{\nu_0}{1+z}\,\frac{[\gamma(t)]^3\,\delta(t)}{10^{12}}\,\left[\frac{n}{10^{-2}\,\mathrm{cm}^3}\right]^{1/2}\mathrm{Hz}, \tag{3}$$

where $\nu_0 \simeq 3.85\times 10^{16}\,\mathrm{Hz} \simeq 160\,\mathrm{eV}$ and $\delta(t)$ is the Doppler factor of the CB. The spectral energy density of the SR from a single CB at a luminosity distance D_L is given by (DDD2009a):

$$F_{CB}[\nu,t] \simeq \frac{\pi\,R^2\,n\,m_e\,c^3\,\gamma(t)^2\,\delta(t)^4\,A(\nu,t)}{4\,\pi\,D_L^2\,\nu_b(t)}\,\frac{p-2}{p-1}\,\left[\frac{\nu}{\nu_b(t)}\right]^{-1/2}\left[1+\frac{\nu}{\nu_b(t)}\right]^{-(p-1)/2}, \tag{4}$$

where $p\sim 2.2$ is the typical spectral index of the Fermi accelerated electrons, and $A(\nu,t)$ is the attenuation of photons of observed frequency ν along the line of sight through the CB, the host galaxy (HG), the intergalactic medium (IGM) and the Milky Way (MW):

$$A(\nu,t) = \exp[-\tau_\nu(\mathrm{CB})-\tau_\nu(\mathrm{HG})-\tau_\nu(\mathrm{IGM})-\tau_\nu(\mathrm{MW})]. \tag{5}$$

The opacity $\tau_\nu(\mathrm{CB})$ at very early times, during the fast-expansion phase of the CB, may strongly depend on time and frequency. The opacity of the circumburst medium [$\tau_\nu(\mathrm{HG})$ at early times] is affected by the GRB and could also be t- and ν-dependent. The opacities $\tau_\nu(\mathrm{HG})$ and $\tau_\nu(\mathrm{IGM})$ should be functions of t and ν, for the line of sight to the CBs varies during the AG observations, due to the hyperluminal motion of CBs.

3.2. The early-time SR

At early-time, before the CB has swept a mass comparable to its rest mass both γ and δ stay put at their initial values γ_0 and δ_0. Then, Eq. (4) yields an early-time SR light curve, $F_{SR}[\nu,t]\propto e^{-\tau_W}\,R^2\,n^{(1+\beta)/2}\,\nu^{-\beta}$. Since $r\propto t$, a CB ejected into a windy density profile, $n\propto 1/r^2$, created by the mass ejection from the progenitor star prior to its SN explosion, emits SR with an early-time light curve,

$$F_{SR}[\nu,t] \propto \frac{e^{-a/t}\,t^{1-\beta}}{t^2+t_{exp}^2}\,\nu^{-\beta} \rightarrow t^{-(1+\beta)}\,\nu^{-\beta}\,. \tag{6}$$

For a CB ejected at time t_i, the time t must be replaced by $t-t_i$, the time after ejection. In the γ-ray and X-ray bands, the SR emission from a CB is usually hidden under the prompt keV-MeV ICS emission. But, in many GRBs, the asymptotic exponential decline of the energy flux density of the prompt keV-MeV ICS emission is taken over by the slower power-law decline, $F_{SR}[\nu,t]\propto t^{-\Gamma_X}\,\nu^{-\Gamma_X+1}$ with $\Gamma_X=\beta_X+1\approx 2.1$ of the synchrotron emission in the windy $\sim 1/r^2$ circumburst density before the CB reach the constant ISM density and the AG enters a plateau phase (see examples, e.g., in DDD2009a). Note that the 'prompt' optical emission that is dominated by SR, decays initially like $F_{SR}[\nu,t]\propto t^{-1.5}\,\nu^{-0.5}$ since the spectral index of the unabsorbed SR emission at frequencies well below the bend frequency is $\beta_O\approx 0.5$. As the wind density decreases with distance, the bend frequency may cross the optical band while the CB is still in the wind, yielding a steeper decay, $F_{SR}[\nu,t]\rightarrow t^{-2.1}\,\nu^{-1.1}$.

3.3. The plateau, the break and the late time decay

During the coasting phase of a CB in a constant density ISM the behaviour of its SR lightcurve as given by Eq. (4) is dominated by the time dependence of its Lorentz factor

$\gamma(t)$. From energy-momentum conservation it follows that

$$\gamma(t) = \frac{\gamma_0}{[\sqrt{(1+\theta^2\,\gamma_0^2)^2 + t/t_0} - \theta^2\,\gamma_0^2]^{1/2}}\,, \tag{7}$$

with

$$t_0 = \frac{(1+z)\,N_{\rm B}}{8\,c\,n\,\pi\,R^2\,\gamma_0^3}\,. \tag{8}$$

This deceleration law is for the case in which the ISM particles re-emitted fast by the CB are a small fraction of the flux of the intercepted ones. As can be seen from Eq. (7), γ and δ change little as long as $t \ll t_b = [1+\gamma_0^2\,\theta^2]^2\,t_0$ which results in the shallow decline/plateau phase of the AG. In terms of typical CB-model values of γ_0, R, $N_{\rm B}$ and n,

$$t_b = (1300\,{\rm s})\,[1+\gamma_0^2\,\theta^2]^2\,(1+z)\left[\frac{\gamma_0}{10^3}\right]^{-3}\left[\frac{n}{10^{-2}\,{\rm cm}^{-3}}\right]^{-1}\left[\frac{R}{10^{14}\,{\rm cm}}\right]^{-2}\left[\frac{N_{\rm B}}{10^{50}}\right]. \tag{9}$$

For $t \gg t_b$, γ and δ decrease like $t^{-1/4}$. The transition $\gamma(t) \sim \gamma_0 \rightarrow \gamma \sim \gamma_0\,(t/t_0)^{-1/4}$ induces a bend (the so called 'jet break') in the synchrotron AG from a plateau to an asymptotic power-law decay,

$$F_{SR}[\nu, t] \propto t^{-p/2-1/2}\,\nu^{-p/2} = t^{-\beta-1/2}\,\nu^{-\beta} = t^{-\Gamma+1/2}\,\nu^{-\Gamma+1}, \tag{10}$$

with a power-law in time steeper by half a unit than that in frequency.

4. The X-ray lightcurve of the afterglow of GRB090618

The X-ray lightcurve of GRB090618 (Evans et al. 2008) shows the canonical behaviour predicted by the CB model (e.g. DDD2002; DDD2009a) and displayed by many Swift GRBs (e.g., Nousek et al. 2006). This behaviour is well reproduced by the CB model as shown in Fig. 1. The fast decline phase with a rapid spectral softening is that predicted for ICS of glory light (e.g. Dado, Dar and De Rújula 2008a; DDD2009a): $F_{ICS}[\nu, t] \rightarrow t^{-2}\,e^{-E\,t^2/E_p\,t_p^2}$. where t and t_p are measured relative to the beginning of the last large prompt emission episode (we used a best fit value, $t_p = 12.9$). The sharp transition around 300 s to a shallow decline/plateau phase with a constant hardness ratio is produced when the synchrotron afterglow given by Eq. (4) takes over. The shape of the SR afterglow of GRB090618 was reproduced with three best fitted parameters, $\gamma_0\,\theta = 1.10$ and $t_0 = 312$s which yield $t_b = 1540$s and $p = 2.08$, This best fit value of p satisfies well the CB model relation, $p = 2\Gamma - 2 = 2.02 \pm 0.10$, where we used the photon spectral index Γ=2.008 (+0.047, -0.046) that was reported in the Swift repository (Evans et al. 2008). The 'jet break' takes place when the jet of CBs gathers a mass comparable to its rest mass (DDD2002; DDD2008b; DDD2009a) as given by Eqs. (8) and (9). The post-break power-law decay of the AG is well described (DDD2008b) by Eq. (10).

5. The optical AG of GRB 090618 and emergence of an underlying SN?

The late time optical AG can be estimated by extrapolating the post break power-law decay to the time of the anticipated emergence of an SN signature akin to that of SN1998bw at the burst location. However, unlike the X-ray light curve which was inferred from a continuous follow-up measurements with the same telescope (Swift XRT), the optical lightcurve of GRB090618 constructed from reported measurements in GCNs with different telescopes at different times, locations, atmospheric and seeing conditions, calibrations and spatial resolutions. In particular, the detection of the SN signature depends on a precise subtraction of the host galaxy contribution to the observed lightcurve. In view of all that we preferred to best fit the early-time observational data on the optical afterglow which were reported in the GCNs listed in Table I and to use the CB model with the parameters determined from the X-ray AG and the early time observational data (Table I) on the optical AG of GRB090618 to predict the late time R-band lightcurve of the optical transient. A host galaxy contribution of r=22.7±0.3 (Malesani et al. 2009) was subtracted from the last two data points, and the anticipated SN1998bw-like contribution at the host location was dimmed by the Galactic extinction along the line of sight corresponding to E(B-V)=0.09. The results of this exercise are presented in Fig. 2.

Although the very early optical emission does not directly affect the late-time behaviour of the AG, we have also fitted the very early ('prompt') optical emission in a windy environment as given by Eq. (6), for completeness and in order to demonstrate the validity of the CB model. The fit to the two prompt emission peaks was obtained with β_O=0.50, t_i=25.1s, a=1.47s, t_{exp}=19.4s for the first peak and t_i=52.4s, a=98s, t_{exp}=40.3s for the second. The scarcity of data points during the rise part of the peaks allows for other equally good fits.

A careful subtraction of the host galaxy contribution from the optical lightcurve of GRB090618 measured with large telescopes of good spatial resolution should have shown already (on June 29, 2009) spectroscopic and photometric evidence for an underlying supernova if its brightness is similar to that of SN1998bw. As of today, the R band lightcurve should show a plateau with a very small rise towards a shallow maximum around July 10, when an SN akin to SN1998bw with only little extinction in the host galaxy will reach its peak brightness of magnitude $\sim$ 23.2 in the R band. The detailed data on the broadband afterglow of GRB090618, which is less bright than that of GRB030329, can still provide another useful test of the long-duration GRB-SN association and of GRB models.

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Table 1. GCNs Reporting Follow-up R-band Optical Observations of GRB090618 Before June 25, 2009

GCN	Telescope	Reported by	Comments
9512	Swift UVOT	Schady et al.	Finding exposure
9513	Palomar 60-inch	Cenko et al.	
9514	KAIT	Perley et al.	
9515	ROTSE-III	Rujopakarn et al.	Earliest Detection
9517	KAIT	Li et al.	Follow-up
9518	Lick 3-m	Cenko et al.	Redshift Measurement
9519	OAGH 2.1-m	Carraminana et al.	Follow-up
9520	Faulkes	Melandri et al.	Follow-up
9522	Mt. Lemmon 1-m	Im. et al.	Follow-up
9526	SDSS	Malesani	Host Detection
9531	Liverpool	Cano et al.	Follow-up
9539	Shajn	Rumyantsev et al.	Follow-up
9542	SAO RAS 6-m	Fatkhullin et al.	Spectroscopy
9548	RTT 1.5-m	Galeev et al.	Follow-up
9575	SARA 0.9-m	Updike et al.	Follow-up
9576	Himalayan 2-m	Anupama et al.	Follow-up

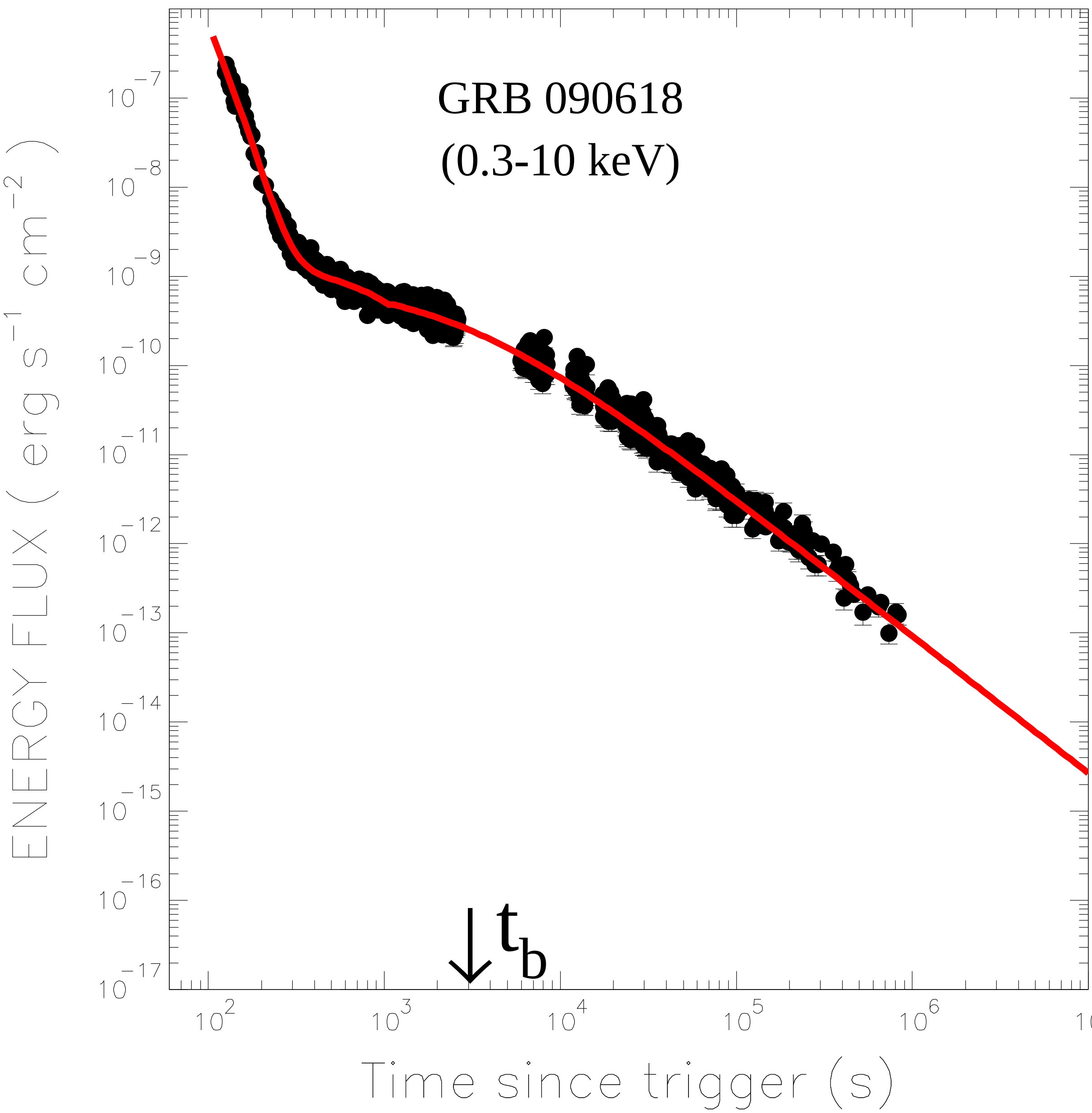

Fig. 1.— Comparison between the Swift XRT lightcurve of GRB090618 (Evans et al. 2009) and its CB model description (see text). The time of the deceleration bend/break t_b is indicated by a down-pointing arrow.

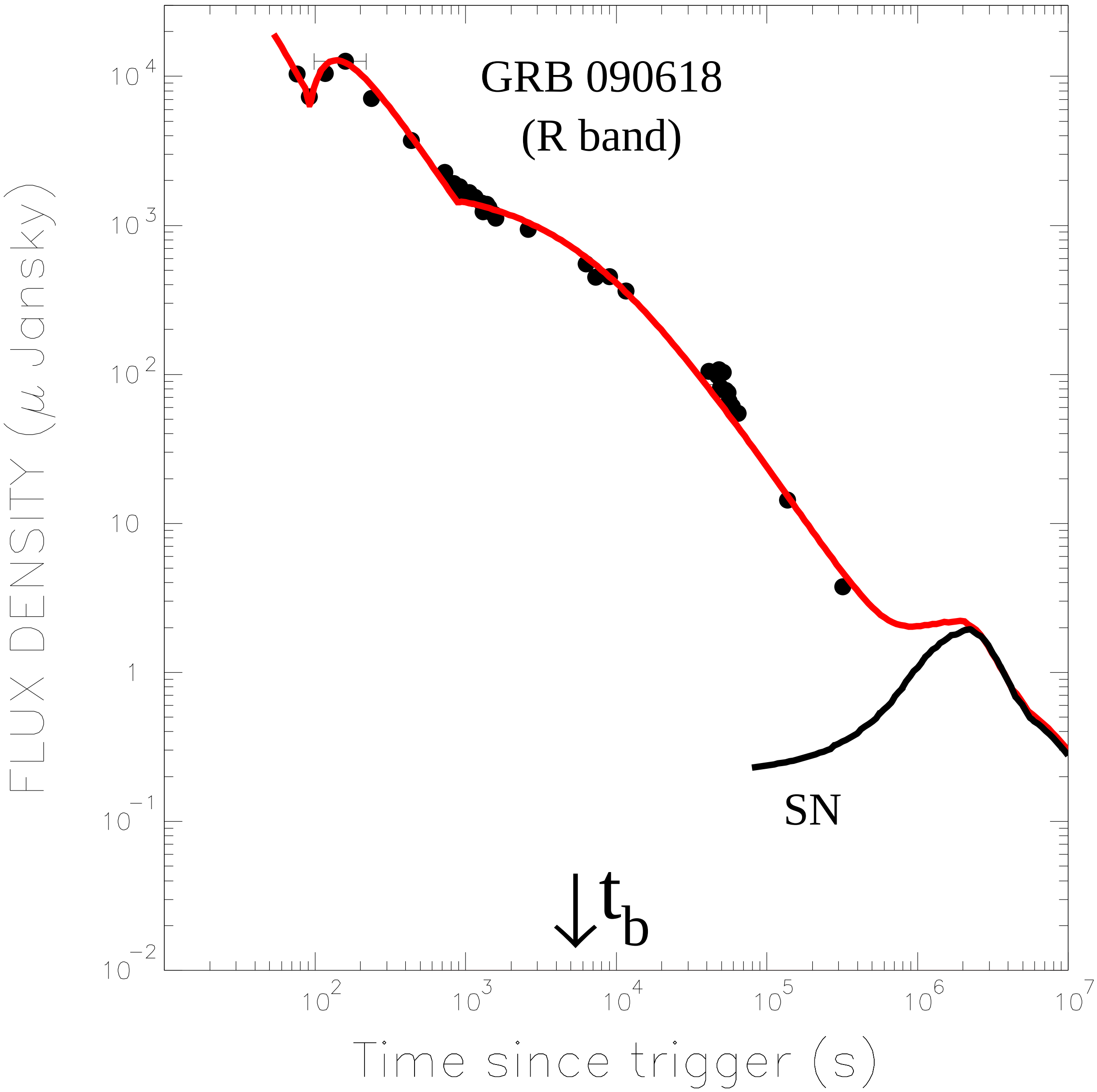

Fig. 2.— Comparison between the R band lightcurve of GRB090618 extracted from the GCN circulars listed in Table I and its CB model description in terms of the parameters which were extracted from the CB model fit to its early X-ray lightcurve measured by the Swift XRT (Evans et al. 2009). The plotted SN lightcurve is that of SN1998bw at the burst location. Its maximum brightness is expected around July 10.